

UNITED STATES PATENT APPLICATION

Title:

DEVICE / HOST COORDINATED PREFETCHING STORAGE SYSTEM

Inventors:

Knut S. Grimsrud
Amber D. Huffman

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Prepared by:
Richard C. Calderwood
Reg. No. 35,468

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1 **DEVICE / HOST COORDINATED PREFETCHING STORAGE SYSTEM**

2 **Background of the Invention**

3 Technical Field of the Invention

4 This invention relates generally to data storage systems, and more particularly to a storage
5 system in which prefetching decisions are made by the storage device, taking advantage of
6 information which the storage device has but which the host is unlikely to have, such as rotational
7 position or what data are already cached by the storage device.

8 Background Art

9 Prefetching can improve system performance, by making data available earlier or faster than
10 would be the case without prefetching. The greater the differences between the rates at which data
11 can be read from a mass storage device such as a hard disk, and the rates at which that data can then
12 be transferred to the processing system, the greater the benefit from prefetching. The more
13 intelligently the prefetching is performed, the more benefit it will offer.

14 FIG. 1 illustrates a data processing system 10 such as is typical in the prior art. The system
15 includes a processor 12 for performing logic operations of the system, a memory controller 14 for
16 interfacing the processor to a memory 16 such as one or more subsystems of dynamic random access
17 memory (DRAM), static random access memory (SRAM), read only memory (ROM), programmable
18 read only memory (PROM), flash memory, and the like. The system further includes a host disk
19 controller 18 for interfacing to a storage system 20 such as one or more of a hard disk drive (HDD),
20 compact disc read only memory (CD-ROM), floppy disk drive, digital video disc (DVD), or the like,
21 or even non-rotating storage such as a tape drive or a solid state bulk storage system.

22 The memory typically includes an application program 22 which performs operations desired
23 by a user. The application runs on an operating system (OS) 24 which provides a higher-level
24 abstraction and collection of routines for performing operations of the system, such as requests to
25 open a file on the storage system. The memory typically also includes one or more drivers
26 customized for operating various hardware systems of the data processing system, including a host
27 storage driver 26 for the particular storage system.

28 When the application wants to, for example, read a portion of a file from the storage system,
29 the application allocates an application buffer 28 which is an area of memory in which the requested
30 data are to be stored. After allocating the application buffer, the application issues an OS call

1 identifying the requested data and indicating the address of the application buffer to which the data
2 are to be retrieved. If the OS has previously cached the requested data in an OS cache 30, such as a
3 file system cache, the OS will simply copy the data from the OS cache to the application buffer and
4 tells the application that the data retrieval has succeeded. If the requested data are not in the OS
5 cache, the OS issues a call to the host storage driver. The driver may maintain a driver cache 32 and,
6 if the requested data are found in the driver cache, the driver copies the requested data directly from
7 the driver cache into the application buffer.

8 The storage system includes a storage drive 36 which may be any suitable mechanism such as
9 one or more rotating hard disk platters, CD-ROM platters, DVD platters, and so forth, and/or one or
10 more non-rotating mechanisms such as tape drives, solid state memory devices, and the like. The
11 storage drive may include one or more data read devices such as a hard disk head mechanism
12 (generally shown as "H"). The storage system includes one or more controllers such as a spin/seek
13 controller 38 for controlling the various storage drives.

14 The storage system also includes a microcontroller 40 for performing logic operations of the
15 storage system, and a storage controller memory 42 for holding data used in those logic operations.
16 The storage controller memory may include registers 44 for passing parameters to or from the driver,
17 and a storage buffer 46 through which requested data are delivered. The storage system may include
18 a variety of prefetch algorithms 48 which the microcontroller executes in attempting to improve
19 overall system performance by intelligently guessing which data are likely to be requested in the near
20 future. The microcontroller can store prefetched data in a storage cache 50. Then, if that data is
21 subsequently requested by the driver, the data can be transferred at the interface rate of the host disk
22 controller, rather than at the typically much slower transfer rate of the storage drive, and without
23 waiting for the head to seek to the correct cylinder and the platter to rotate to the correct sector.

24 Data actually requested may be termed "demand data", and speculatively prefetched data may
25 be termed "prefetch data".

26 FIGS. 1 and 2 illustrate operation of the storage system. The seek/spin controller moves the
27 head to the correct cylinder of the platter. At some time during the next full rotation of the platter, the
28 requested block will pass beneath the head and be read into the storage buffer.

29 Unfortunately, existing prefetch schemes are either completely host driven or completely
30 device driven, with no coordination between the host and the device. The host storage driver or the
31 OS determines that some particular data, such as block 63 are likely to be needed next, and issues a

1 “prefetch request”. If, while the storage system is servicing this prefetch request and is, for example,
2 waiting for the disk to rotate to the correct track, the host issues a demand request for a different
3 block, the demand request will be stalled until the prefetch request has been completed. This is
4 especially problematic in systems in which the storage accesses are largely non-sequential, such as
5 Windows desktop workloads.

6 Another problem can arise in prefetching schemes which automatically expand the scope of
7 demand data requests to include prefetch data. These prefetch data are typically data which are
8 previous and/or subsequent blocks contiguous to the demand blocks. If the host gets lucky, there is
9 no problem. Often, however, the previous (prefetch) blocks may have started rotating past the head
10 moments before the head was in position to read them; for example in FIG. 2 if the demand request
11 block is block 62 and the driver decides to also fetch blocks 61 and 63 as prefetch data. The result is
12 that the device disk controller will have to wait nearly a complete revolution of the platter before it
13 can begin reading the data, which begins with block 61 that has just passed the head, even though the
14 demand request block 62 itself has not yet begun passing the head. In this instance, the prefetch is
15 very negatively efficient.

16 Yet another problem can arise when the host storage driver has asked for a prefetch block
17 which is logically mapped to a physical block (such as block 64) which is “bad” and which has been
18 remapped by the storage system to a different location (such as block 65) that is unknown to the host.
19 Any requests to such blocks are likely to cause delays, because they are likely to mean moving the
20 head to a different track, perhaps one far removed from the track of the demand request block.

21 Still another problem can arise when the host storage driver asks for prefetch data that go
22 beyond the end of the current track and causes the request to cross a cylinder boundary. This causes a
23 head seek and results in a negatively efficient prefetch.

24 In any of these situations, if the host storage driver had known more information about the
25 state of the storage system, such as which track and sector the head were at, or which data were
26 already in the storage cache, it might not have issued the prefetch request, or may have modified it,
27 or may have delayed it.

28 **Brief Description of the Drawings**

29 The invention will be understood more fully from the detailed description given below and
30 from the accompanying drawings of embodiments of the invention which, however, should not be

1 taken to limit the invention to the specific embodiments described, but are for explanation and
2 understanding only.

3 FIG. 1 shows a data processing system according to the prior art, including its storage system.

4 FIG. 2 shows a simplified view of a rotating storage device, illustrating locations of demand
5 request blocks and prefetch blocks.

6 FIG. 3 shows one embodiment of a data processing system according to this invention.

7 FIG. 4 shows one embodiment of a host disk buffer and associated registers.

8 FIG. 5 shows another embodiment of the invention.

9 FIG. 6 shows a flowchart of one embodiment of a method of operation of this invention.

10 FIG. 7 shows a flowchart of another embodiment of a method of operation of this invention.

11 Detailed Description

12 FIGS. 3 and 4 illustrate one exemplary embodiment of a system 100 according to this
13 invention. The decision of what prefetch data to return, if any, can be made by the enhanced storage
14 system 102 rather than solely by the host. Because the driver 104 or other host entities may not know
15 beforehand whether prefetch data will be returned with the demand data, nor how much prefetch
16 data, nor where the prefetch data and demand data are in the driver buffer 106, the system includes a
17 mechanism for the storage system to provide this information.

18 In one embodiment of the invention, a demand offset register 108 is set by the storage system
19 to indicate where in the driver buffer the demand data begins, and a fetched size register 110 is set by
20 the storage system to indicate how much data (prefetch and demand) was returned into the driver
21 buffer. In various embodiments, these registers may reside in various locations, such as in the host
22 memory 16, or in the storage controller memory 42, or other suitable location. In other embodiments,
23 the identifying information specifies the prefetch data, rather than the demand data; thus the demand
24 data are specified indirectly.

25 The storage system may have returned one or more prefetch blocks 120 (such as block 62 of
26 FIG. 2) which are sequentially prior to one or more demand blocks 122 (such as block 63 of FIG. 2),
27 and one or more prefetch blocks 124 (such as block 64 of FIG. 2) which are sequentially after the
28 demand blocks. These blocks may or may not have completely filled the driver buffer; if not, there
29 will be an unused area 126 in the driver buffer.

30 The beginning address (DrvBufAddr) of the driver buffer 106 is predetermined, in some
31 embodiments. In other embodiments, the driver buffer can be dynamically allocated, and located via

1 a pointer, for example. The beginning of the demand data can, in one embodiment, be found by
2 adding the beginning address of the driver buffer and the effective value (DemOffset) of the demand
3 offset register. In some embodiments, the offset, size, and so forth are specified in bytes, while in
4 other embodiments, they are specified in sectors; the address calculations are made taking this into
5 account. The end of the demand data is determined by adding the demand size to the address of the
6 beginning of the demand data, minus one. Summing the address of the driver buffer, the demand
7 offset, and the demand size gives the starting address of the prefetch data that follows the demand
8 data. Summing the driver buffer address and the contents of the fetched size register (FetchedSize)
9 minus one gives the end of the prefetch data.

10 Other buffer indexing or addressing schemes are, of course, readily available. For example, a
11 table could be generated by the storage system, such as the following:

12 <block offset> <block type>
13 <block offset> <block type>
14 <block offset> <block type>
15 ...
16 <block offset> <block type>
17 <end marker>

18 in which a <block offset> is an offset from the start of the driver buffer (or, alternatively, an actual
19 address in the memory), a <block type> indicates whether the block is prefetch data or demand data,
20 and the <end marker> indicates the end of the table. As another alternative, the table could be
21 implemented as linked list. These and other possibilities are well within the abilities of ordinary
22 skilled storage engineers, and will be appreciated upon having the teachings of this disclosure.

23 With an enhanced host driver in place, the storage system can utilize improved prefetching
24 algorithms 112. This is especially true in embodiments in which the driver and storage system are
25 adapted to recognize a "fetch" instruction which is distinct from a normal "read" instruction. In some
26 such embodiments, the fetch instruction may simply be a degenerate case of the read instruction in
27 which no (null) demand data are specified.

28 The improved prefetch algorithms are able, because they reside in the storage system rather
29 than in the host, to take advantage of improved knowledge about the state of the storage system. For
30 example, if the host has asked for demand block 63, and the prefetch algorithms determine that the
31 platter rotation has already passed potential prefetch block 61 when the head arrives in the correct

1 track, the prefetch algorithm can begin prefetching with block 62 instead of block 61. Similarly, if
2 the host has asked for demand block 63, and the prefetch algorithms determine that blocks 63 and 64
3 are already in the storage cache, the storage system can immediately return demand block 63 and
4 prefetch block 64 at the interface rate, and not wait for any additional data from the storage drive. Or,
5 if the host has asked for demand block 63, and demand block 63 must be retrieved from the storage
6 drive, the prefetch algorithms can determine that prefetching should not include block 64 because
7 block 64 has been remapped to block 65, which would cause a long delay for head seek.

8 In general, when the demand data must be read from the storage drive, prefetch blocks that
9 are prior to the demand blocks (relative to the rotation of the storage drive) can essentially be
10 prefetched at no cost, as long as the head has not passed them when it becomes ready to read in the
11 correct track. Typically, the interface will be available, and these prefetched blocks can be transferred
12 to the host at the media rate before the demand blocks even become available at the head. However,
13 prefetch blocks that are after the demand blocks (relative to the rotation) cannot be prefetched for
14 free, as they are not available until after the demand blocks have already been read. Any extra time
15 spent waiting for them to become available from the storage drive is additional delay before the host
16 can be informed that the transfer is complete, and before the fetched size register can be written. In
17 some scenarios, it may nevertheless be desirable to prefetch them. Also, if these later prefetch blocks
18 are available in the storage cache, they may be sent nearly for free, with only enough additional delay
19 incurred per the interface rate limit.

20 The "fetch" command can be used even in the absence of any demand data request. It
21 essentially tells the storage system "if you have prefetched or cached data that you think might be
22 useful to me, go ahead and send them". It will be especially advantageous to respond to "fetch"
23 requests using only data that are in the storage cache or storage buffer, and not data that must be read
24 from the drive, so the request can be fulfilled at the interface rate and completed much earlier than if
25 the drive were read.

26 In another embodiment, the storage system returns prefetch data that are not contiguous with
27 the demand data. Ideally, this prefetch data will already be in the storage cache, so no extra seek/spin
28 delay is incurred.

29 The host and the storage system may be termed a "data requestor" and a "data source",
30 respectively.

1 FIG. 5 illustrates another embodiment of a system 140 according to this invention, and more
2 particularly illustrates that the invention is not necessarily limited to local host environments such as
3 a personal computer and its directly attached disk drive. The system 140 includes a data requestor
4 142 coupled to a data source 144 over a communication link 146. The data requestor can be any
5 entity which requests data from storage, such as a personal computer, a server, a home appliance, a
6 website, a cellular telephone, and so forth. The data source can be any entity which stores requestable
7 data, such as a server, a website, a disk drive, a memory subsystem, a network-attached storage
8 (NAS) apparatus, and so forth. The communication link connecting them can be one or more of any
9 suitable data communication means, such as a local area network (LAN), a wide area network
10 (WAN), a wireless link, Ethernet, a cellular telephone system, a telephone system, a circuit-switched
11 network, a packet-switched network, satellite, laser, fiber optic, the internet, and so forth.

12 The data requestor includes a data destination buffer 148 (corresponding roughly to the driver
13 buffer of FIG. 3, for example) and storage 150 (corresponding roughly to the demand offset register
14 and fetched size register of FIG. 3, or the table indicated above, for example) for one or more data
15 identifiers which enable the data requestor to sort out the various parts of prefetch data and demand
16 data received from the data source. The data source includes a storage buffer 152 (corresponding
17 roughly to the storage buffer of FIG. 3), one or more prefetch algorithms 154 (corresponding roughly
18 to the prefetch algorithms of FIG. 3), a storage cache 156 (corresponding roughly to the storage
19 cache of FIG. 3), and a storage drive 158 (corresponding roughly to the storage drive of FIG. 3).

20 The data requestor issues a "read" command or a "fetch" command, and the data source
21 responds with prefetch data and/or demand data as determined by the prefetch algorithms and the
22 state of the data source (which is typically unavailable to the data requestor, at least in a meaningful
23 time frame).

24 In some embodiments, the storage system may "push" prefetch data without being asked by
25 the host or data requestor, such as through a direct memory access (DMA) protocol.

26 FIG. 6 illustrates one exemplary method 200 of operation of a system constructed according
27 to the principles of this invention. The application calls (202) the OS to allocate memory for data.
28 The OS allocates (204) the requested size of memory area, and returns the address of the allocated
29 memory to the application. The application calls (206) the OS to read data into that memory from the
30 storage system. The OS calls (208) the driver to read the data from the storage system, and provides
31 the address of the allocated memory to the driver. The driver tells (210) the storage system which

1 demand blocks to read, and gives the storage system the address of the driver's buffer memory. The
2 storage system decides (212) which blocks to prefetch and return with the demand blocks, according
3 to the prefetch algorithms and state of the storage system. The storage system writes (214) the
4 resulting data blocks to the driver's buffer. The storage system writes (216) the data identifiers (such
5 as the demand offset register and the fetched size register), and signals (218) the driver that the data
6 read has been completed. The driver uses (220) the data identifiers to find the demand blocks in the
7 buffer, and copies (222) the demand blocks to the application's allocated memory location. The
8 driver tells (224) the OS that the demand data is ready, and the OS tells (226) the application that the
9 data is ready. While the application uses the demand data, the driver is free to take care of various
10 housekeeping operations, including caching (228) any prefetch data blocks that were returned with
11 the demand data blocks.

12 FIG. 7 illustrates another method 250 of operation of a system according to the invention.
13 The driver tells (252) the storage system which demand blocks (DB) to read. If (254) the storage
14 system determines, by its prefetch algorithms, that both the demand blocks and the prefetch blocks
15 (PB) are already in the storage cache, the storage system sends (256) them to the driver. Otherwise, if
16 (258) the demand blocks are already in the storage cache, only the demand blocks are sent (260) to
17 the driver. If not, then if (262) the prefetch blocks are in the storage cache (but the demand blocks are
18 not), the storage system sends (264) the prefetch blocks. But if the prefetch blocks are not cached, if
19 (266) they are available for free (or at an acceptable penalty, per the prefetch algorithms), the
20 prefetch blocks are read (268) from the drive storage and are sent (270) to the driver. Then, the data
21 blocks are read (272) from the drive storage and sent (274) to the driver. After ("A") the storage
22 system sends whatever data are to be sent, the driver copies (276) the demand blocks to the
23 application's allocated memory buffer, using the identifiers provided by or retrieved from the storage
24 system. Then, the driver caches (278) any prefetch blocks that were sent, again using the identifiers.

25 The reader should appreciate that drawings showing methods, and the written descriptions
26 thereof, should also be understood to illustrate machine-accessible media having recorded, encoded,
27 or otherwise embodied therein instructions, functions, routines, control codes, firmware, software, or
28 the like, which, when accessed, read, executed, loaded into, or otherwise utilized by a machine, will
29 cause the machine to perform the illustrated methods. Such media may include, by way of illustration
30 only and not limitation: magnetic, optical, magneto-optical, or other storage mechanisms, fixed or
31 removable discs, drives, tapes, semiconductor memories, organic memories, CD-ROM, CD-R,

1 CD-RW, DVD-ROM, DVD-R, DVD-RW, Zip, floppy, cassette, reel-to-reel, or the like. They may
2 alternatively include down-the-wire, broadcast, or other delivery mechanisms such as Internet, local
3 area network, wide area network, wireless, cellular, cable, laser, satellite, microwave, or other
4 suitable carrier means, over which the instructions etc. may be delivered in the form of packets,
5 serial data, parallel data, or other suitable format. The machine may include, by way of illustration
6 only and not limitation: microprocessor, embedded controller, PLA, PAL, FPGA, ASIC, computer,
7 smart card, networking equipment, or any other machine, apparatus, system, or the like which is
8 adapted to perform functionality defined by such instructions or the like. Such drawings, written
9 descriptions, and corresponding claims may variously be understood as representing the instructions
10 etc. taken alone, the instructions etc. as organized in their particular packet/serial/parallel/etc. form,
11 and/or the instructions etc. together with their storage or carrier media. The reader will further
12 appreciate that such instructions etc. may be recorded or carried in compressed, encrypted, or
13 otherwise encoded format without departing from the scope of this patent, even if the instructions
14 etc. must be decrypted, decompressed, compiled, interpreted, or otherwise manipulated prior to their
15 execution or other utilization by the machine.

16 Reference in the specification to "an embodiment," "one embodiment," "some
17 embodiments," or "other embodiments" means that a particular feature, structure, or characteristic
18 described in connection with the embodiments is included in at least some embodiments, but not
19 necessarily all embodiments, of the invention. The various appearances "an embodiment," "one
20 embodiment," or "some embodiments" are not necessarily all referring to the same embodiments.

21 If the specification states a component, feature, structure, or characteristic "may", "might", or
22 "could" be included, that particular component, feature, structure, or characteristic is not required to
23 be included. If the specification or claim refers to "a" or "an" element, that does not mean there is
24 only one of the element. If the specification or claims refer to "an additional" element, that does not
25 preclude there being more than one of the additional element.

26 Those skilled in the art having the benefit of this disclosure will appreciate that many other
27 variations from the foregoing description and drawings may be made within the scope of the present
28 invention. Indeed, the invention is not limited to the details described above. Rather, it is the
29 following claims including any amendments thereto that define the scope of the invention.